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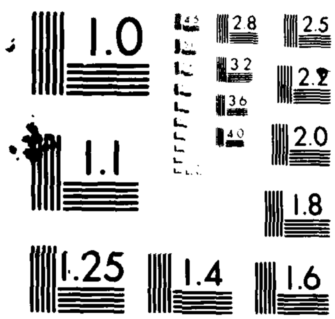

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A Method Of Predicting The Interference Margin For Non-Directional Beacons

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December 1981

U.S. Department of Transportation
Federal Aviation Administration

NOTICE

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16. Abstract

The purpose of this report is to describe a new method for determining the electric field strength produced by a Non-Directional Beacon (NDB) as a function of the important parameters involved which include distance, frequency, ground conductivity, and effective isotropic radiated power (EIRP). This method enables the determination of the coverage area within which the signal level from the NDB exceeds some critical value, usually 70 microvolts per meter (peak power). Applied to another NDB which might cause interference to the first, correcting for frequency difference to account for receiver selectivity, one can determine at any point the interference margin, (i.e., the amount by which the desired NDB signal exceeds the undesired and potentially interfering signal). This interference margin must be at least 15 dB for satisfactory operation. The scope of this report includes frequencies from 190 to 535 kHz.

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ENGLISH/METRIC CONVERSION FACTORS

LENGTH

To / From	Cm	m	Km	in	ft	s mi	n mi
Cm	1	0.01	1×10^{-5}	0.3937	0.0328	6.21×10^{-6}	5.39×10^{-6}
m	100	1	0.001	39.37	3.281	0.0006	0.0005
Km	100,000	1000	1	39370	3281	0.6214	0.5395
in	2.540	0.0254	2.54×10^{-5}	1	0.0833	1.58×10^{-5}	1.37×10^{-5}
ft	30.48	0.3048	3.05×10^{-4}	12	1	1.89×10^{-4}	1.64×10^{-4}
S mi	160,900	1609	1.609	63360	5280	1	0.8688
n mi	185,200	1852	1.852	72930	6076	1.151	1

AREA

To / From	Cm^2	M^2	Km^2	in^2	ft^2	$S\ mi^2$	$n\ mi^2$
Cm^2	1	0.0001	1×10^{-10}	0.1550	0.0011	3.86×10^{-11}	5.11×10^{-11}
m^2	10,000	1	1×10^{-6}	1550	10.76	3.86×10^{-7}	5.11×10^{-7}
Km^2	1×10^{10}	1×10^{6}	1	1.55×10^{9}	1.08×10^{7}	0.3861	0.2914
in^2	6.452	0.0006	6.45×10^{-10}	1	0.0069	2.49×10^{-10}	1.88×10^{-10}
ft^2	929.0	0.0929	9.29×10^{-8}	144	1	3.59×10^{-8}	2.71×10^{-8}
$S\ mi^2$	2.59×10^{10}	2.59×10^{6}	2.590	4.01×10^{9}	2.79×10^{7}	1	0.7548
$n\ mi^2$	3.43×10^{10}	3.43×10^{6}	3.432	5.31×10^{9}	3.70×10^{7}	1.325	1

VOLUME

To / From	Cm^3	Liter	m^3	in^3	ft^3	yd^3	fl oz	fl pt	fl qt	gal
Cm^2	1	0.001	1×10^{-6}	0.0610	3.53×10^{-5}	1.31×10^{-6}	0.0338	0.0021	0.0010	0.0002
liter	1000	1	0.001	61.02	0.0353	0.0013	33.81	2.113	1.057	0.2642
m^2	1×10^{6}	1000	1	61,000	35.31	1.308	33,800	2113	1057	264.2
in^3	16.39	0.0163	1.64×10^{-5}	1	0,0006	2.14×10^{-5}	0.5541	0.0346	2113	0.0043
ft^3	28,300	28.32	0.0283	1728	1	0.0370	957.5	59.84	0.0173	7.481
yd^3	765,000	764.5	0.7646	46700	27	1	25900	1616	807.9	202.0
fl oz	29.57	0.2957	2.96×10^{-5}	1.805	0.0010	3.87×10^{-5}	1	0.0625	0.0312	0.0078
fl pt	473.2	0.4732	0.0005	28.88	0.0167	0.0006	16	1	0.5000	0.1250
fl qt	948.4	0.9463	0.0009	57.75	0.0334	0.0012	32	2	1	0.2500
gal	3785	3.785	0.0038	231.0	0.1337	0.0050	128	8	4	1

MASS

To / From	g	Kg	oz	lb	ton
g	1	0.001	0.0353	0.0022	1.10×10^{-6}
Kg	1000	1	35.27	2.205	0.0011
oz	28.35	0.0283	1	0.0625	3.12×10^{-5}
lb	453.6	0.4536	16	1	0.0005
ton	907,000	907.2	32,000	2000	1

TEMPERATURE

$^{o}F = 9/5\ (^{o}C - 32)$

$^{o}C = 5/9\ (^{o}F) + 32$

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FEDERAL AVIATION ADMINISTRATION
SYSTEMS RESEARCH AND DEVELOPMENT SERVICE
SPECTRUM MANAGEMENT BRANCH

STATEMENT OF MISSION

The mission of the Spectrum Management Branch is to assist the Department of State, National Telecommunications and Information Administration, and the Federal Communications Commission in assuring the FAA's and the nation's aviation interests with sufficient protected electromagnetic telecommunications resources throughout the world and to provide for the safe conduct of aeronautical flight by fostering effective and efficient use of a natural resource - the electromagnetic radio frequency spectrum.

This objective is achieved through the following services:

- Planning and defending the acquisition and retention of sufficient radio frequency spectrum to support the aeronautical interests of the nation, at home and abroad, and spectrum standardization for the world's aviation community.

- Providing research, analysis, engineering, and evaluation in the development of spectrum related policy, planning, standards, criteria, measurement equipment, and measurement techniques.

- Conducting electromagnetic compatibility analyses to determine intra/intersystem viability and design parameters, to assure certification of adequate spectrum to support system operational use and projected growth patterns, to defend aeronautical services spectrum from encroachment by others, and to provide for the efficient use of the aeronautical spectrum.

- Developing automated frequency selection computer programs/routines to provide frequency planning, frequency assignment, and spectrum analysis capabilities in the spectrum supporting the National Airspace System.

- Providing spectrum management consultation, assistance, and guidance to all aviation interests, users, and providers of equipment and services, both national and international.

TABLE OF CONTENTS

CHAPTER I INTRODUCTION

The purpose of this report is to describe a new method for determining the electric field strength produced by a Non-Directional Beacon (NDB) as a function of the important parameters involved which include distance, frequency, ground conductivity, and effective isotropic radiated power (EIRP). This method enables the determination of the coverage area within which the signal level from the NDB exceeds some critical value, usually 70 microvolts per meter (peak power). Applied to another NDB which might cause interference to the first, correcting for frequency difference to account for receiver selectivity, one can determine at any point the interference margin, (i.e., the amount by which the desired NDB signal exceeds the undesired and potentially interfering signal). This interference margin must be at least 15 dB for satisfactory operation. The scope of this report includes frequencies from 190 to 535 kHz.

The currently applied FAA Handbook (1) was written in 1965, and has several practical shortcomings which make a revision advisable. While the effects of ground conductivity and frequency on radio wave propagation in this frequency range are complex, all of the pertinent propagation data was condensed into just one figure, which makes the data difficult to use and understand. As perhaps an unavoidable result of this condensation, the explanations and directions for applying the propagation curves and determining the appropriate signal levels contained in paragraphs 33 through 39 are somewhat difficult to apply, and do not explain or justify many of the computation steps. The procedure is graphical, with dB values added and subtracted by drawing parallel

lines on graphs rather than by the simpler approach, at least in the opinion of the authors of this report, of straightforward numerical addition and/or subtraction.

In addition to the above criticisms of the basic method of reference 1, it also contains supportive information that is difficult to apply. For example, sky wave effects are discussed, and some numerical information is given, but no criteria is given for applying sky wave information to the general process of determining signal levels. Also, the discussion of determining the EIRP of an NDB is vague and incomplete. Finally, the graphical method of reference 1 is not suitable for computer implementation should this be desired.

In Chapter II of this report a new method for determining signal level and interference margin is presented. The new method is not graphical, but instead involves the algebraic addition and subtraction of decibel signal levels, as is commonly done in the determination of gain margin and fade margin of terrestrial and space communication links. The signal quantities required for the computations are obtained from propagation curves, tables, and knowledge of the EIRP of the station(s) being considered. Examples of the necessary propagation curves are given for 4 different ground conductivities and for sea water, but for completeness the new version of the handbook should include curves for additional ground conductivities. Also included in Chapter II is a table of receiver selectivity vs frequency offset. This table conforms to that in reference 1, but could easily be changed to include the effects of improved ADF receiver performance if necessary.

The effects of sky wave are not included in the new method. Sky

wave effects are limited to large distances at this frequency range, and their inclusion would greatly complicate the NDB frequency assignment problem without a corresponding return in performance reliability (2).

An accurate determination of the effective isotropic radiated power of the NDB under consideration is important for the application of the above method. Chapter III discusses various analytical approaches to this determination, and reaches the conclusion that the best method for determining EIRP is to measure the electric field strength at several locations from 1 to 3 miles from the NDB, use the appropriate propagation curves to relate these measurements to EIRP, and average the results. For situations of low ground conductivity, especially at higher frequencies, a knowledge of the local ground conductivity is important to accurate determination of EIRP from electric field measurements.

CHAPTER II COMPUTATION METHOD

A. Introduction

When assigning the frequency and specifying the Effective Isotropic Radiated Power of a new Non-Directional Beacon, or changing the parameters of an existing beacon, there are two basic constraints which must be met. First, the new or reassigned beacon must not cause interference to other, existing facilities. Second, the new beacon must be capable of providing frequency protected coverage in its assigned service area. This frequency protected coverage consists of two distinct parts. First, the beacon must provide a strong enough signal level so that ADF receivers in an interference-free environment will operate properly. Second, the signals from other existing beacons must not interfere with the operation of ADF receivers tuned to the new beacon in its designated coverage area.

Based on ADF receiver performance, these two constraints can be stated numerically as follows. First, a beacon must provide a signal level of at least 50 μV/meter (34 dB μV/m) within its operation coverage volume at the alarm point. (This is equivalent to 70 μV/m at the peak power point.) Second, the beacon signal must be at least 15 dB above the level of all potential interfering signals after allowing for the selectivity characteristics of the receiver. It has been suspected that the absolute level of the undesired and potentially interfering signal might also be a constraint on beacon frequency and power assignment (3), but more recent work (4) has indicated that such is not the case. Only the ratio of desired to undesired signal (D/U) is considered here.

The currently applied method for assessing 'eacon coverage and interference is the FAA Handbook entitled "Frequency Management Engineering Principles; L/MF Frequency Assignment Criteria" (1). This handbook contains propagation curves, correction factors for frequency, ground conductivity, frequency offset, and other parameters. It describes methods for determining coverage distance (where the desired signal exceeds a certain value, usually 70 μV/meter), and interference distance (where the interfering signal is 15 dB below the desired signal, including correction for receiver selectivity). The method described in this handbook is graphical, and requires simple geometric constructions to be made on propagation curves. While good results can be obtained, the method is cumbersome, and cannot be readily converted to implementation on a computer if desired.

In this chapter a new approach which does not involve any graphical construction is presented. In this approach, values are read from the propagation curves, and these values are algebraically added or subtracted to obtain the desired and undesired signal levels and the desired to undesired (D/U) signal level ratio. This new method can be very readily adapted to computer implementation.

B. Required Propagation Curves and Other Data

In order for the new method to be applied with a minimum of calculation, necessary information can best be presented in graphical and tabulated form. The most extensive set of graphs are shown in Figures 2-1 through 2-5 and contain curves of electric field strength vs distance for 1 Watt EIRP as a function of ground conductivity and frequency. Different curves are given for ground conductivities of 30, 8, 2, and 0.5 millimhos per meter, which range from very good

conductivity to very poor. It is anticipated that in the final version of this method finer increments in ground conductivity would be taken, with different curves given, for example, for conductivities of 30, 15, 8, 4, 2, 1, 0.5, and 0.25 millimhos per meter. For all of these curves the relative permittivity is held constant at 4, since this is an average value, and further since the relative permittivity has only a very minor effect on propagation at these frequencies. In addition to the above, a set of propagation curves for sea water is also given.

Figure 2-6 is a graph which allows easy conversion of EIRP from units of watts to units of dB with respect to 1 watt. This conversion could also be made by evaluating the expression

$$EIRP_{dB/1\ W} = 10 \log_{10} (EIRP_{watts}) \qquad (2\text{-}1)$$

where $EIRP_{dB/1\ W}$ is the desired value of EIRP expressed in dB relative to 1 watt and $EIRP_{watts}$ is the EIRP expressed in watts. This equation is the basis of Figure 2-6.

Table 2-1 contains the correction factors by which the undesired and potentially interfering signal is to be reduced as a function of frequency difference due to the selectivity of the ADF Receivers. This table agrees with the values in reference (1), but could be changed as receiver selectivity is improved.

Figure 2-7 can be used to convert electric field from units of microvolts per meter to dB relative to 1 microvolt per meter. This can also be done using the equation

$$E_{dB} = 20 \log_{10}(E_{\mu V})$$

where E_{dB} is electric field in dB relative to 1 microvolt per meter and $E_{\mu V}$ is electric field in microvolts/meter.

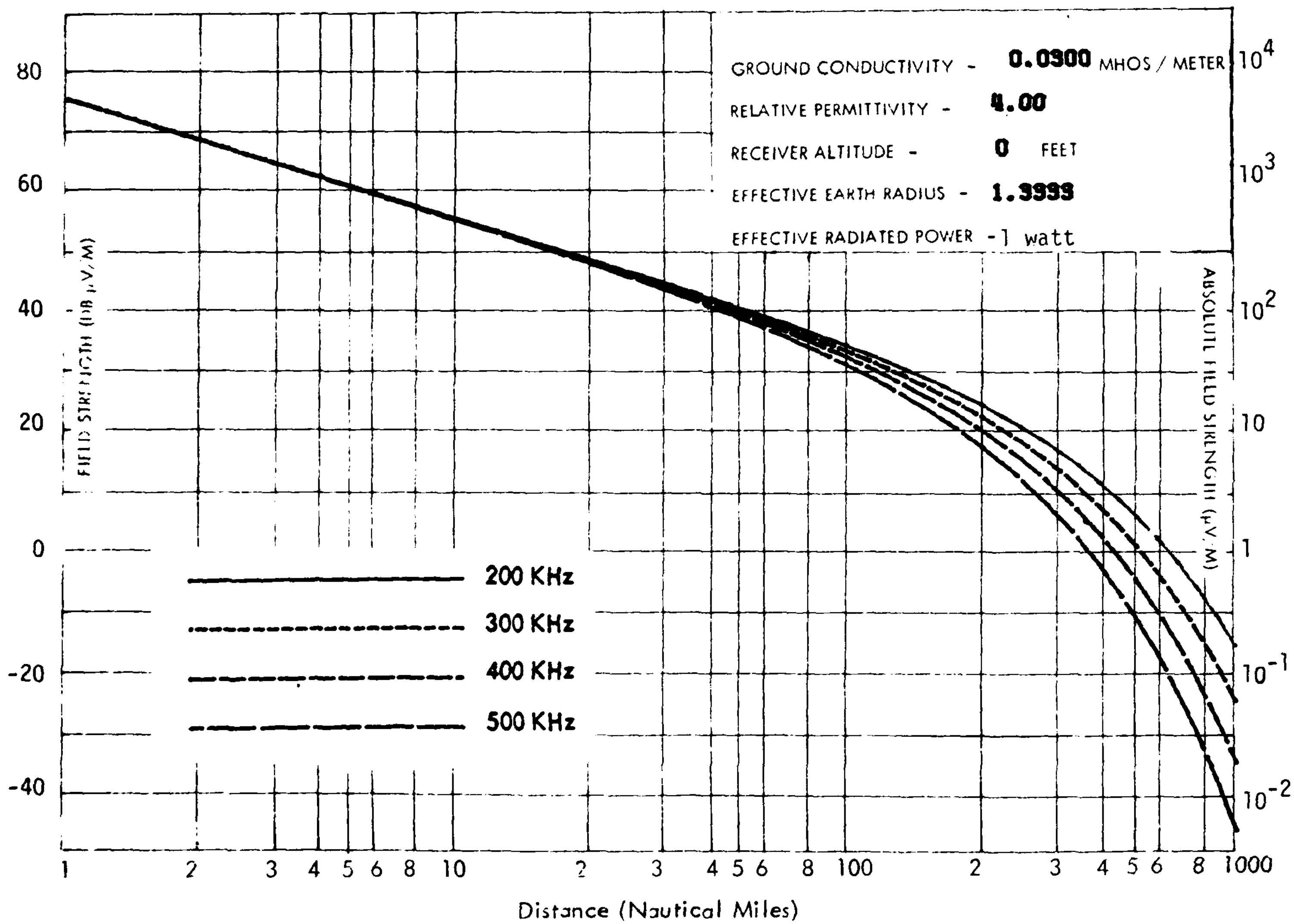

Figure 2-1 Electric field vs Distance from a 1 watt Effective Isotropic Radiated Power transmitting antenna for a ground conductivity of 0.03 mhos/meter.

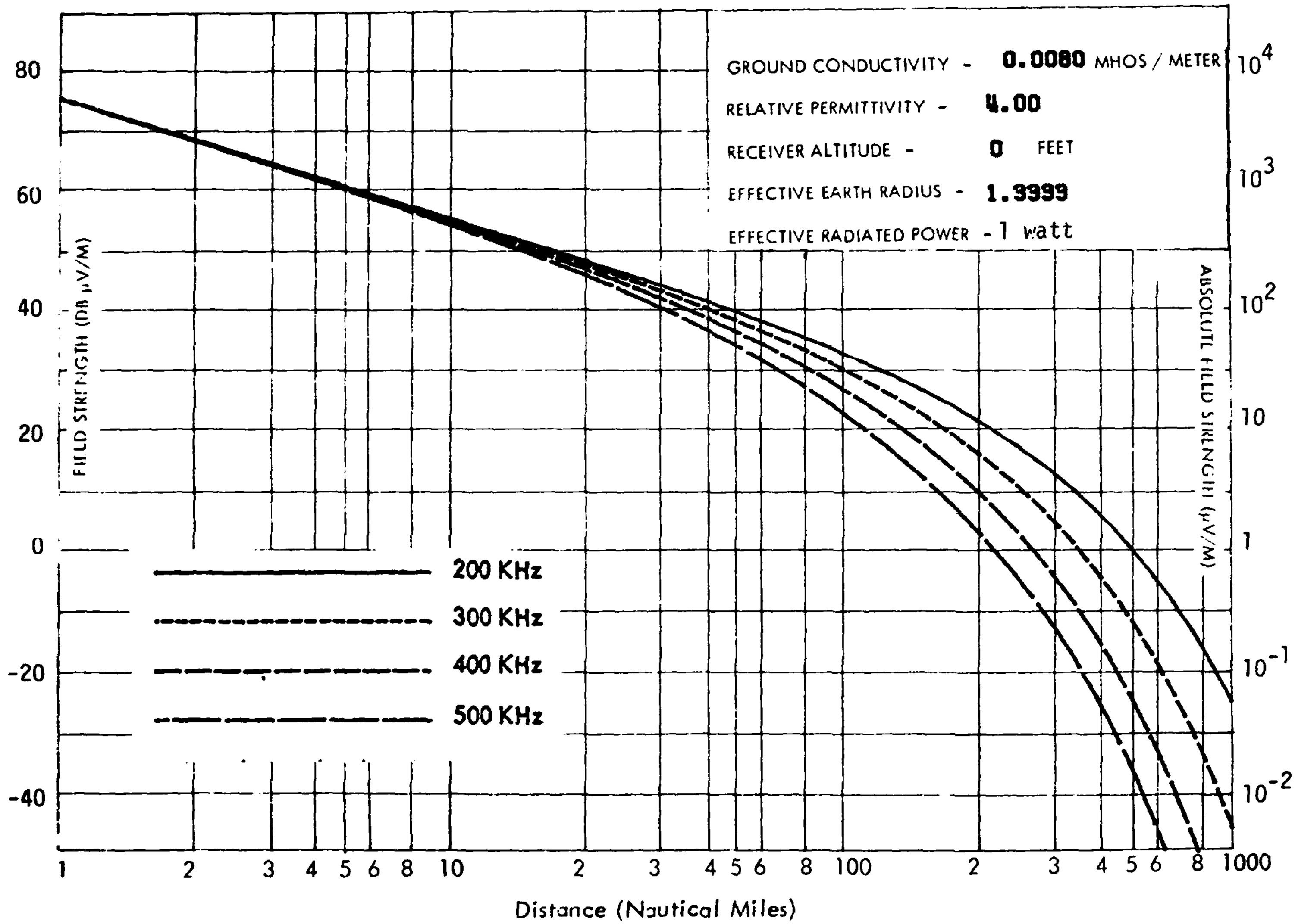

Figure 2-2 Electric field vs Distance from a 1 watt Effective Isotropic Radiated Power transmitting antenna for a ground conductivity of 0.008 mhos/meter.

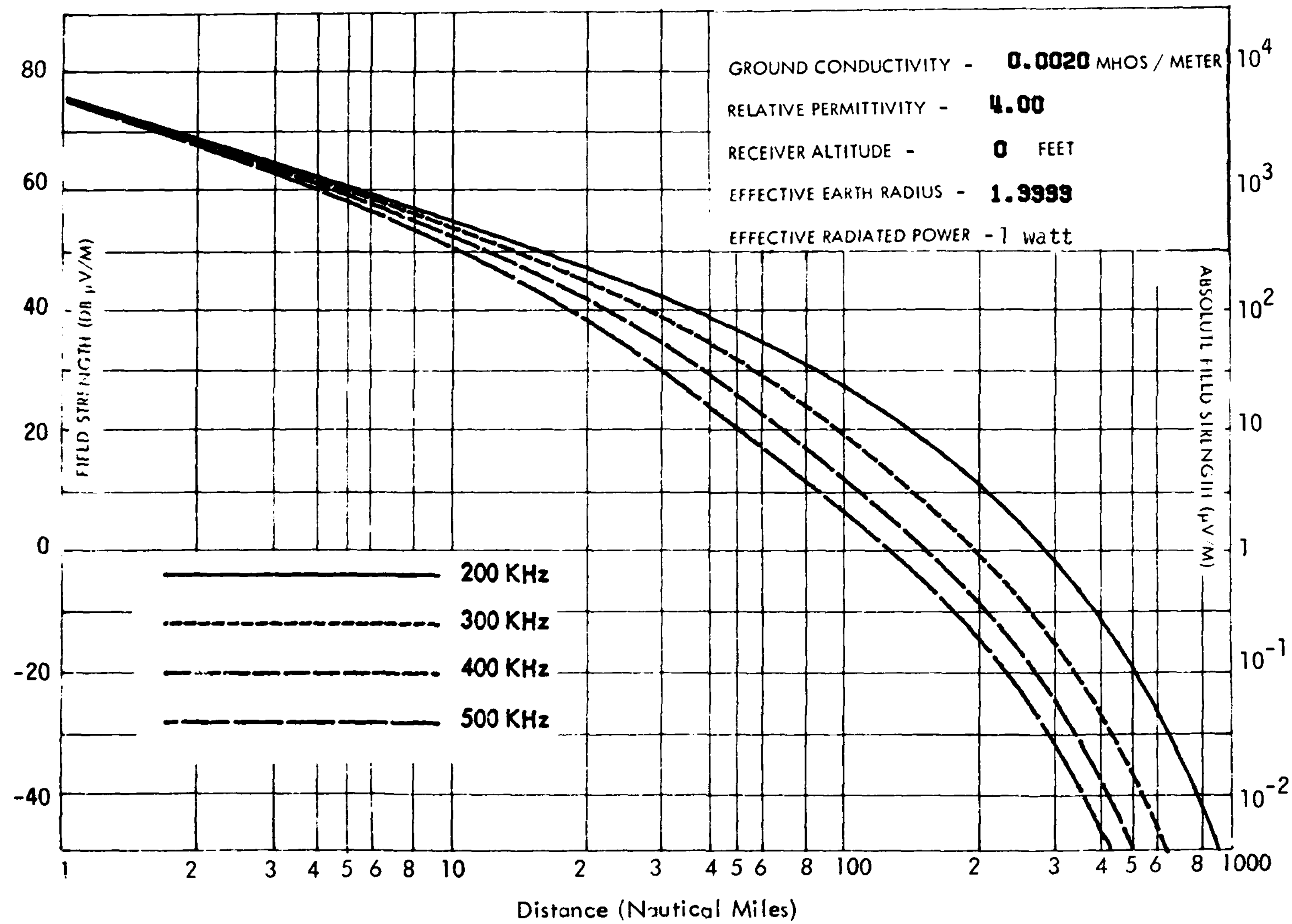

Figure 2-3 Electric field vs Distance from a 1 watt Effective Isotropic Radiated Power transmitting antenna for a ground conductivity of 0.002 mhos/meter

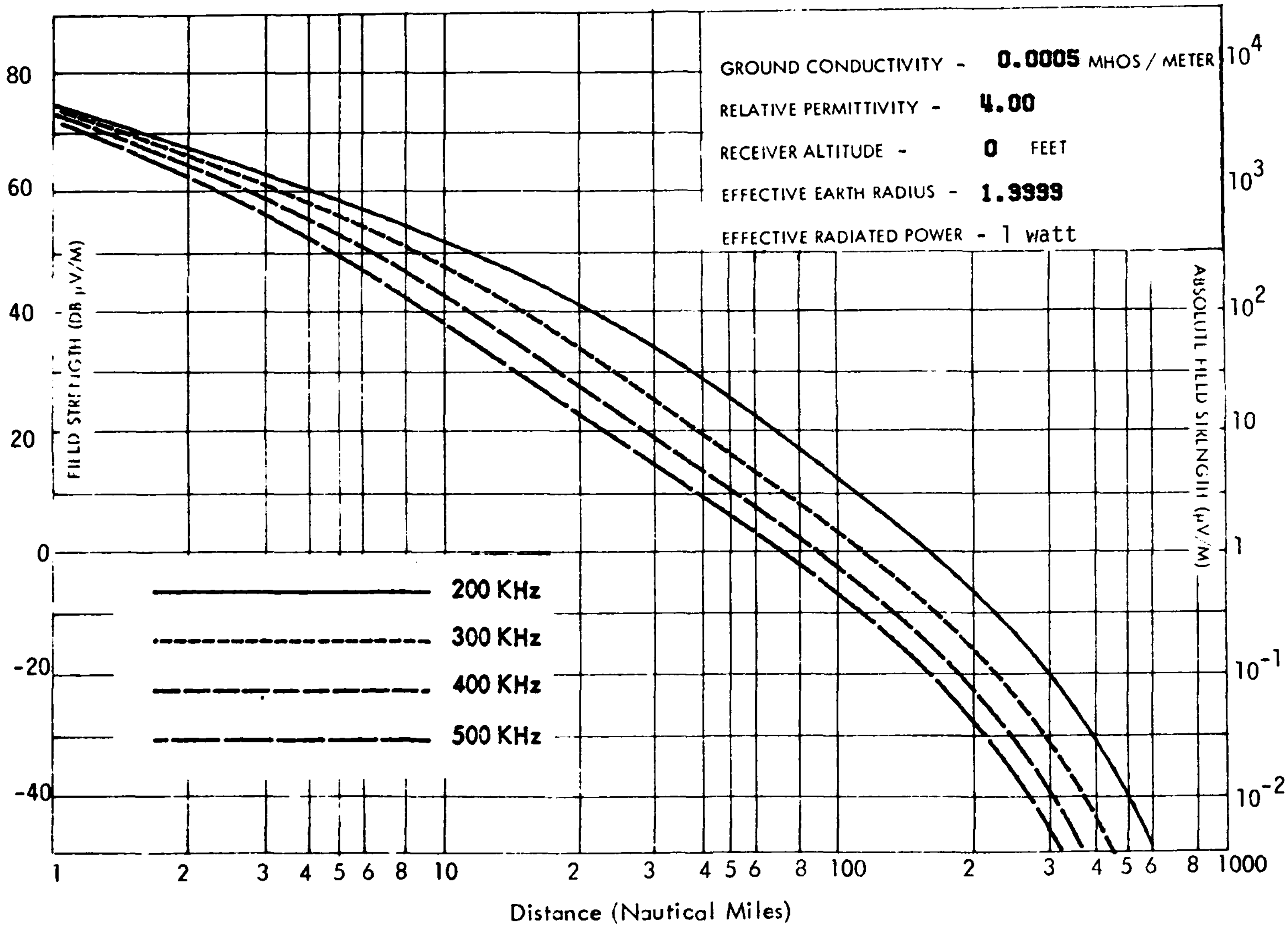

Figure 2-4 Electric field vs Distance from a 1 watt Effective Isotropic Radiated Power transmitting antenna for a ground conductivity of 0.0005 mhos/meter.

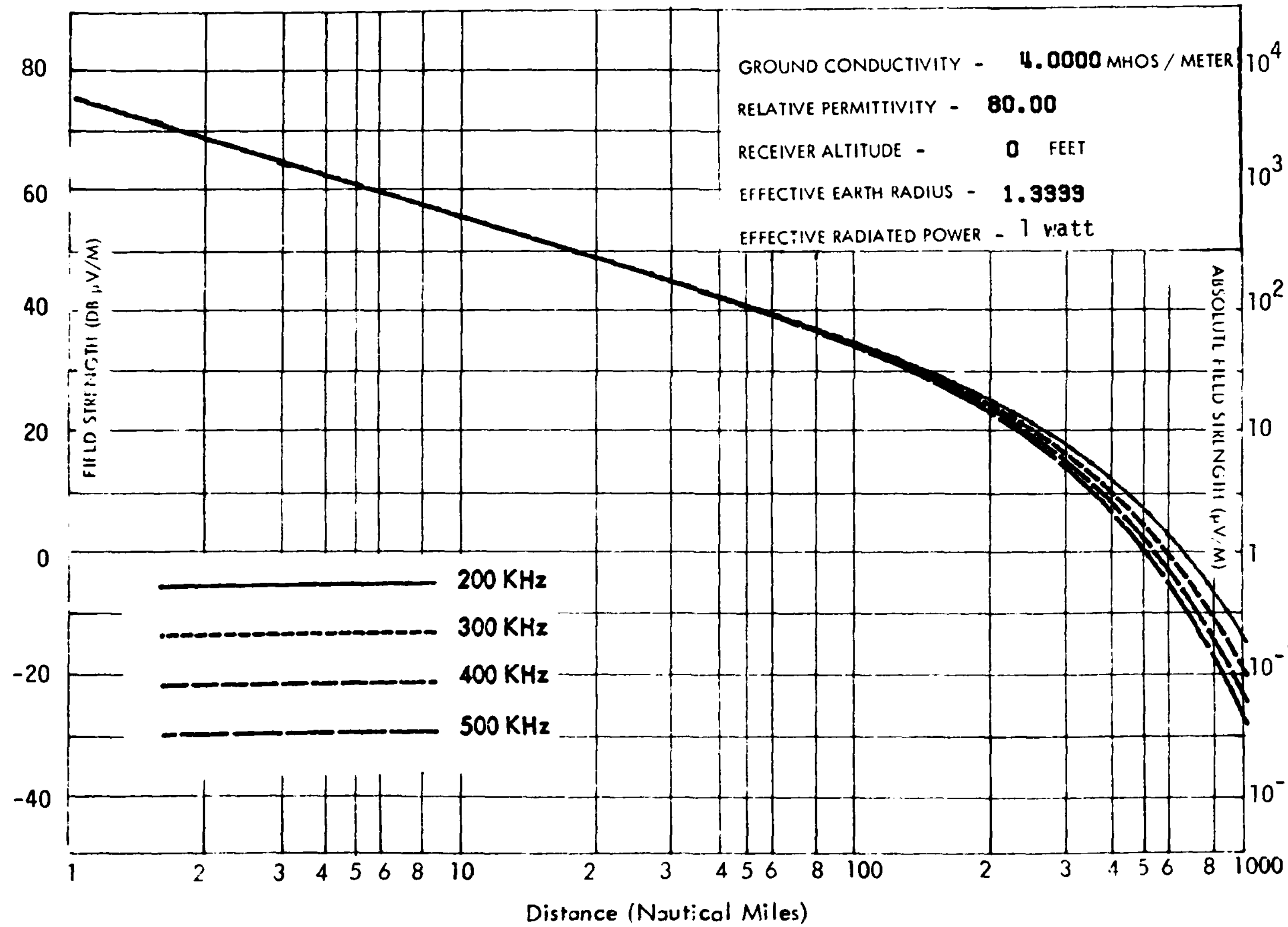

Figure 2-5 Electric field vs Distance from a 1 watt Effective Isotropic Radiated Power transmitting for conductivity 4 mhos/meter, relative permittivity 80, which is approximately that of sea water.

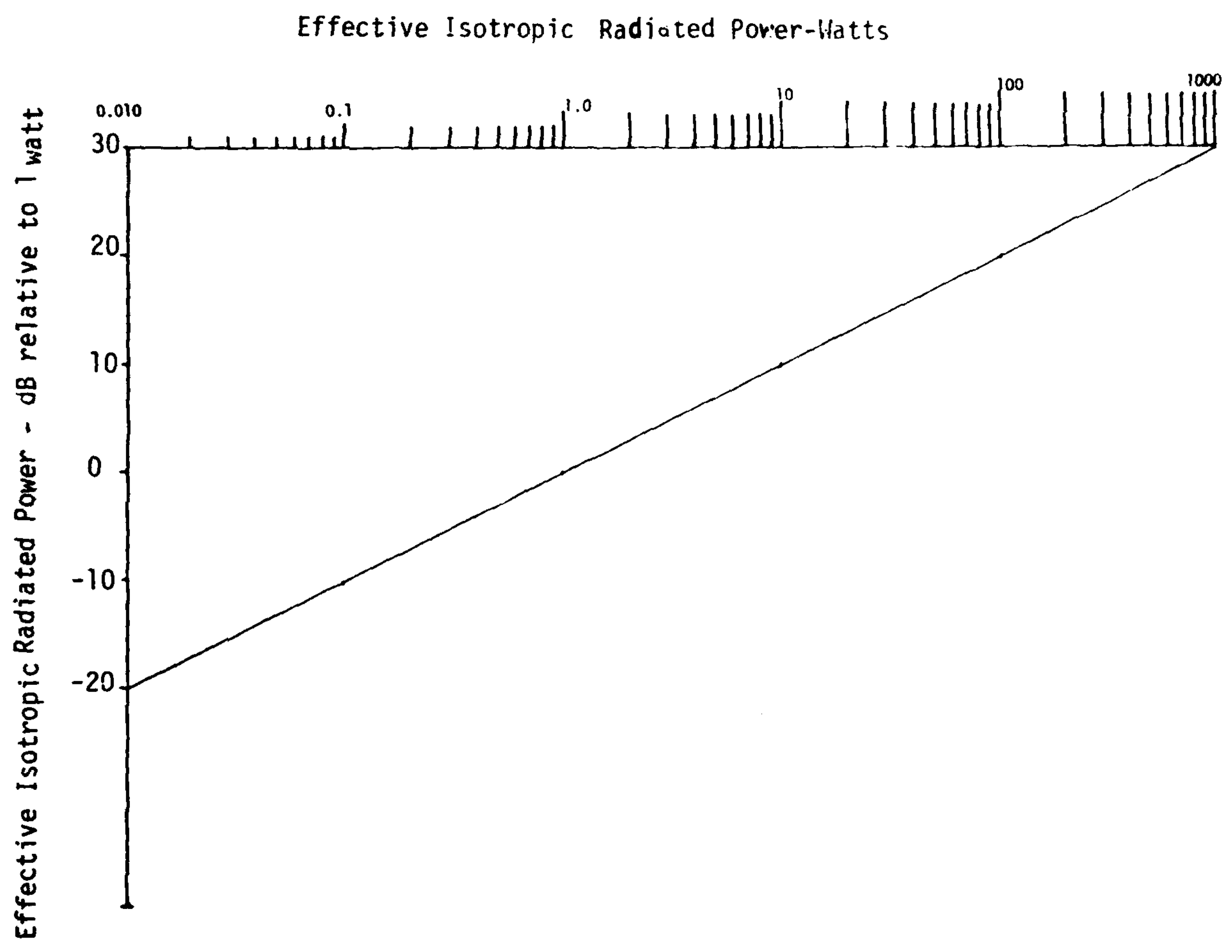

Figure 2-6 Graph for conversion of Effective Isotropic Radiated Power in Watts to Effective Isotropic Radiated Power in dB relative to 1 watt.

Table 2-1

Receiver Selectivity Factor vs Frequency Difference between D and U signals

Frequency Difference	Factor
± 1 KHZ	0 dB
± 2 KHZ	-1 dB
± 3 KHZ	-12 dB
± 4 KHZ	-28 dB
± 5 KHZ	-40 dB
± 6 KHZ	-50 dB

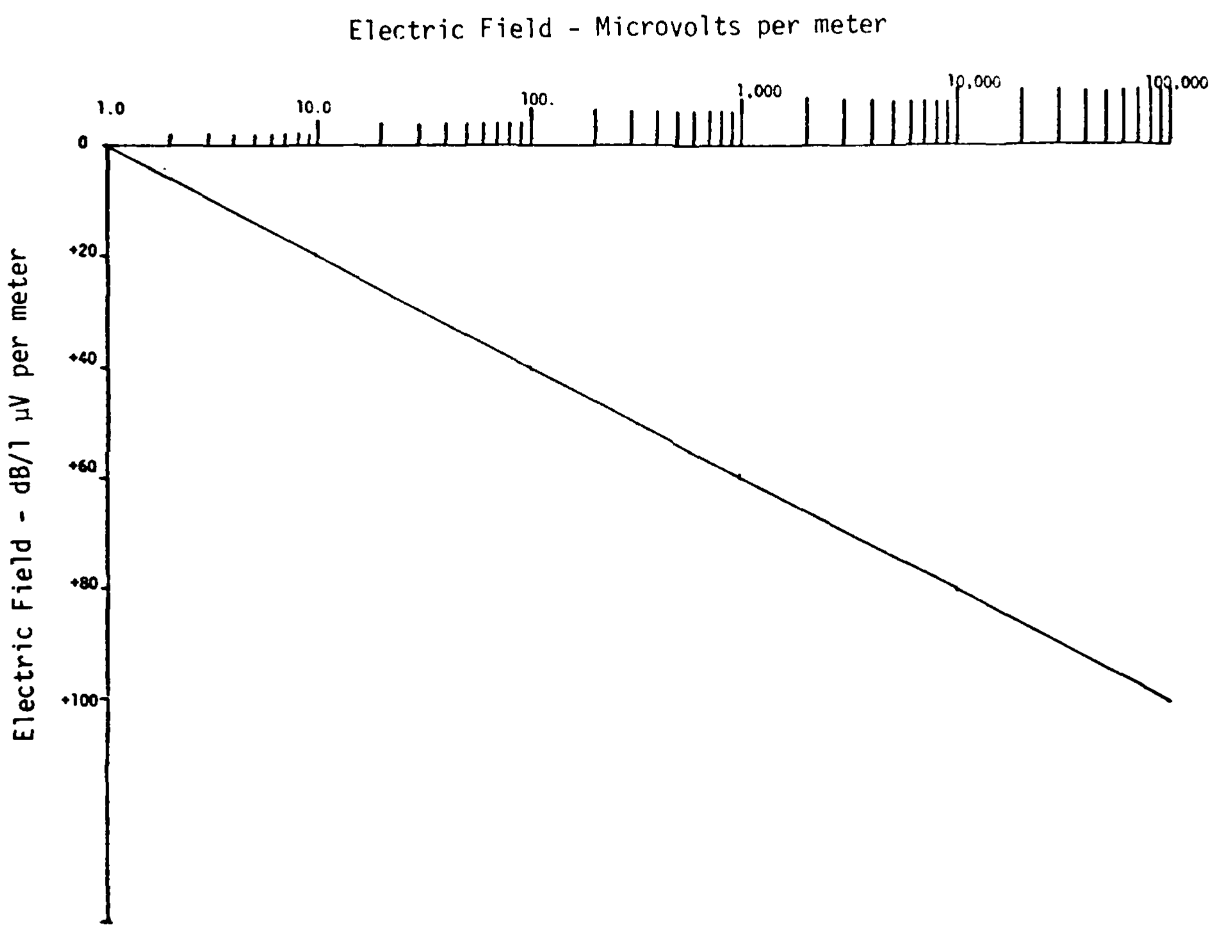

Figure 2-7 Graph for conversion of Electric Field Strength from units of microvolts per meter to units of dB relative to 1 microvolt per meter.

The final information needed is the ground conductivity along the propagation path. This can be estimated from published values, such as are given in Figure 5 of reference 1, or in more extensive tabulations such as in (5).

With this information available, the method for determining desired and undesired signal level which will be described in the next section can be readily applied.

C. Calculation Method

The canonical situation which is to be resolved by the method proposed in this section is as follows. Two beacons are under consideration, one producing the desired signal, the other the undesired and potentially interfering signal. It is assumed that the location, frequency, and EIRP of both stations are known. Further, it is assumed that the coverage limit of the desired signal is known, that is, the maximum distance from the desired signal NDB at which the desired signal must be greater than some critical value, usually 70 volts/meter, and also 15 dB greater than the undesired signal corrected for receiver selectivity. Often other situations may arise such as, for example, when the EIRP necessary for a given desired signal level at a certain distance from the NDB station is to be determined. After presenting the approach to the canonical problem, examples will be given of how the method can be used to deal quite easily with other situations.

The basic format for the proposed method is shown in Figure 2-8. Lines one to three are concerned with determining the desired signal at a certain distance from the desired signal NDB. Lines four through seven are concerned with determining the undesired signal level at a

Determination of Desired and Interfering Signal Levels

Desired Signal Level

EIRP = _____ watts = _____ dB/1 W (Figure 2-6) (enter also on line 2)

Conductivity = _____ millimhos/meter

Distance to Coverage Limit = _____ Nautical Miles (corresponds to line 1)

Frequency = _____ kHz.

1) Signal at Coverage Limit for 1 W EIRP (from figures 2-1 through 2-5) _____ dB/ µV/meter

2) Adjustment to Actual EIRP _____ dB/ 1 W

3) Desired (D) Signal Level _____ dB / µV/meter
(line 3 = line 1 + line 2)

For 70 µV/m, D must be at least 37 dB/ µV/meter

Undesired Signal Level

EIRP = _____ watts = _____ dB/1 W (enter also on line 5)

Conductivity = _____ millimho/meter

Distance to D signal coverage limit = _____ Nautical Miles (corresponds to line 4)

Frequency = _____ kHz

4) Signal at D Coverage Limit for 1 W EIRP _____ dB/ µV/meter

5) Adjustment to Actual EIRP _____ dB/1 W

6) Receiver Selectivity Factor (Table 2-1) _____ dB

7) Effective Undesired (U) Signal Level _____ dB/µV/meter
(line 7 = line 4 + line 5 + line 6)

8) D - U = _______ (line 3) - _______ (line 7) = _____ dB Interference Margin

For Interference Protection, D-U must be at least 15 dB
(All additions must be algebraic)

Figure 2-8 Calculation format for new method of determing Electric Field Strength and Interference Margin for Non-Directional Beacons.

certain distance from the undesired signal NDB, corrected for receiver selectivity. Line 8 combines the above results to determine the desired/undesired signal ratio.

To illustrate the approach, let us consider an example worked in Figure 2-9. The geometry is shown in Figure 2-10. This is the canonical problem situation, and the initially unknown quantities which are found after application of the method are circled on the figure. Beginning at the top of the figure, the desired signal NDB parameters are listed. For this example it is assumed that the EIRP is known in units of dB/1 W. Methods for determining the EIRP of an actual NDB are discussed in the next chapter of this report.

The computation of the desired signal level requires three steps. First, read the electric field which would be produced at the coverage limit distance by a 1 watt EIRP radiator, for the given conditions of frequency and ground conductivity, from the appropriate figure which contains the propagation curves for the given ground conductivity. For this example, from Figure 2-2, which applies for 8 millimhos/meter, read 45 dB μV/meter at a distance of 25 nautical miles, interpolating between the 300 and 400 kHz curves. Enter this value on line 1. Next, on line 2 enter the actual EIRP value expressed in dB/ 1 W. Finally, to obtain the desired (D) signal level at the coverage limit add algebraically lines 1 and 2 to obtain line 3. For 70 microvolts per meter, this result must be 37 dB μV/meter or greater. For this example the desired signal exceeds the minimum by 2 dB at the desired coverage limit.

Let us consider the possibility of interference by the undesired signal. Again referring to Figure 2-9, the parameters of the undesired

Example 1

Desired Signal Level

EIRP = 0.25 watts = -6 dB/1 W (Figure 2-6)(enter also on line 2)

Conductivity = 8 millimhos/meter

Distance to Coverage Limit = 25 Nautical miles (corresponds to line 1)

Frequency = 345 kHz.

1)	Signal at Coverage Limit for 1 W EIRP (from figures 2-1 through 2-5)	45 dB/ μV/meter
2)	Adjustment to Actual EIRP	-6 dB/ 1 W
3)	Desired (D) Signal Level (line 3 = line 1 + line 2)	39 dB/ μV/meter

For 70 μV/m, D must be at least 37 dB/ μV/meter

Undesired Signal Level

EIRP = 1.6 watts = +2 dB/1 W (enter also on line 5)

Conductivity = 8 millimho/meter

Distance to D signal Coverage limit = 60 Nautical miles (corresponds to line 4)

Frequency = 341 kHz

4)	Signal at D Coverage Limit for 1 W EIRP	36 dB/ μV/meter
5)	Adjustment to Actual EIRP	+2 dB/ 1 W
6)	Receiver Selectivity Factor (Tabel 2-1)	-28 dB
7)	Effective Undesired (U) Signal Level (line 7 = line 4 + line 5 + line 6)	10 dB/ μV/meter

8) D - U = $\underset{\text{(line 3)}}{39}$ - $\underset{\text{(line 7)}}{10}$ = 29 dB Interference Margin

For Interference protection, D-U must be at least 15 dB

(All additions must be algebraic)

Figure 2-9 Sample Calculation Number 1.

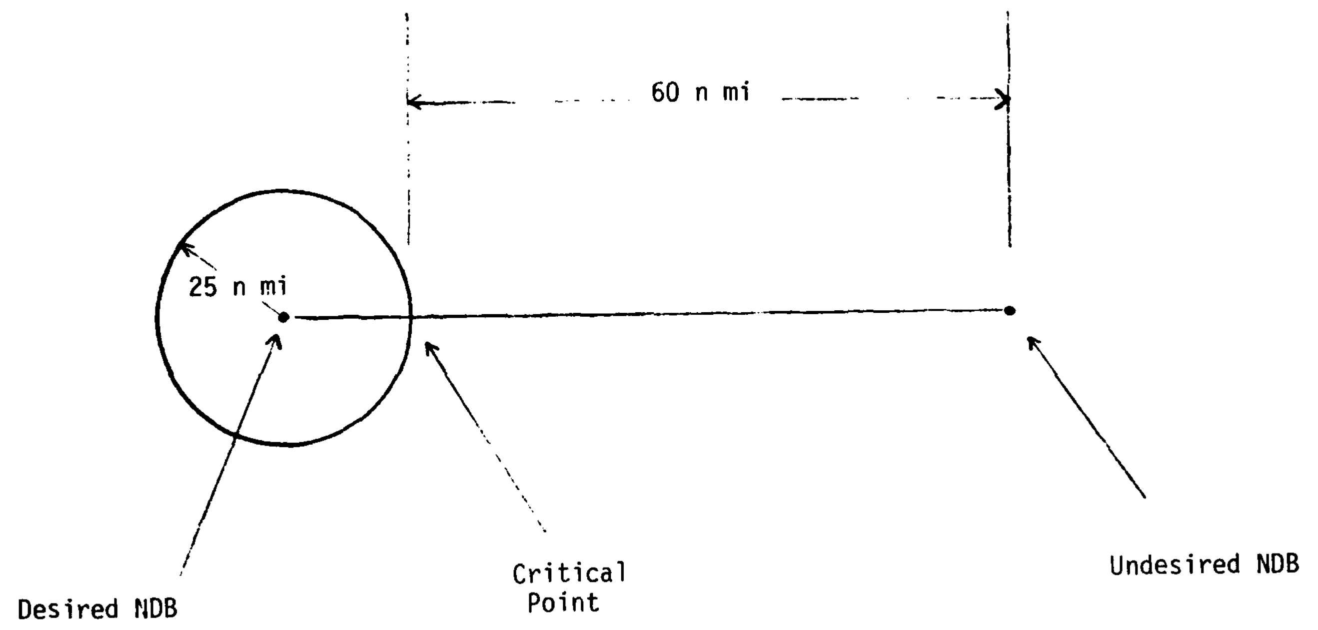

Figure 2-10 The Situtation Considered in Example 1

signal are entered on the form. The entry for line 4 is read, for 8 millimhos, from Figure 2-2 for 60 miles, the EIRP is entered on line 5, and the receiver selectivity correction for a 4 kHz frequency difference is entered from Table 2-1. Line 7 is the algebraic sum of lines 4, 5, and 6. Finally, the desired to undesired (D/ U) signal ratio is determined to be 29 dB by subtracting algebraically line 7 from line 3. Since this is greater than 15 dB, there will be no interference from this undesired signal. And thus, for this particular combination of NDB stations, satisfactory operation of the 345 kHz NDB will be achieved for the given coverage limit. The resulting interference margin will be 39 - 10 dB or 29 dB at the coverage limit. The roles of the two stations (desired and undesired) would have to be checked in reverse before an assignment could be made.

While the preceeding example illustrates the application of the proposed computation method to the fundamental, canonical situation of determining desired and undesired signal levels for a pair of NDB's with given EIRP's, frequencies, etc., at a given distance, the current Handbook (1) gives examples for other situations, one of which is the determination of rated coverage. In this application, it is desired to find the distance from an NDB with given EIRP, frequency, etc., at which the electric field strength will be 70 microvolts/meter. An example of applying the new proposed method to the determination of rated coverage is given in Figure 2-11. Again, the initially unknown quantities which are obtained as a result of the application of the analysis method are circled. The electric field strength given on line 1) of example 2 is the equivalent signal at the coverage limit for a 1 W NDB and is obtained by setting line 3 at 37 dB/ μV/meter (70 microvolts/meter), with line 1 being obtained as the algebraic differ-

Example 2 - Rated Coverage

Desired Signal Level

EIRP = 0.25 watts = -6 dB/1 W (Figure 2-6)(enter also on line 2)

Conductivity = 8 millimhos/meter

Distance to Coverage Limit = 27 Nautical Miles (corresponds to line 1)

Frequency = 345 kHz.

1)	Signal at Coverage Limit for 1 W EIRP (from figures 2-1 through 2-5)	43 dB/ μV/meter
2)	Adjustment to Actual EIRP	-6 dB/ 1 W
3)	Desired (D) Signal Level	37 dB / μV/meter

(line 3 = line 1 + line 2)

For 70 μV/m, D must be at least 37 dB/ μV/meter

Undesired Signal Level

EIRP = ____ Watts = ____ dB/1 W (enter also on line 5)

Conductivity = _____ millimho/meter

Distance to D signal Coverage Limit = ____ Nautical miles (corresponds to line 4)

Frequency = _____ kHz

4)	Signal at D Coverage Limit for 1 kW EIRP	_____ dB/ μV/meter
5)	Adjustment to Actual EIRP	_____ dB/1 W
6)	Receiver Selectivity Factor (Table 2-1)	_____ dB
7)	Effective Undesired (U) Signal Level	_____ dB/ μV/meter

(line 7 = line 4 + line 5 + line 6)

8) D - U = _______ (line 3) - _______ (line 7) = _____ dB Interference Margin

For Interference protection, D-U must be at least 15 dB
(all additions must be algebraic)

Figure 2-11 Sample Calculation Number 2.

ence between line 3 and line 2. The result obtained on line 1, 43 dB/ μV/meter, is then used in conjunction with Figure 2-2, for the given 8 millimhos/meter conductivity, to determine the rated coverage as 27 miles.

Another situation discussed in the current Handbook is the determination of service radius, interference radius, and minimum geographic separation, as shown in Figure 2-12. Service radius is essentially the same concept as rated coverage, except that the minimum electric field strength used to determine the service radius need not be 70 microvolts/meter. The interference radius is the distance from the undesired NDB required to bring its electric field strength to 15 dB below the minimum level required for the desired signal in its coverage area. Example 3 illustrates the determination of these quantities for the same pair of NDB stations considered in Example 1, and is shown in Figure 2-13. Figure 2-13a shows the results for the 345 kHz NDB considered as the desired station, with the further requirement that within its service radius its electric field strength must be at least 40 dB above 1 microvolt/meter (100 microvolts/meter). As for Example 2, line 1 is determined from the algebraic difference of lines 3 and 2, with the corresponding service radius found from Figure 2-2 as 22 miles. The interference radius is found by setting line 7 to 25 dB μV/meter, the difference between line 3 (40 dB/ 1 μV/m) and 15 dB, and forming line 4 as the algebraic difference between line 7 and the algebraic sum of lines 5 and 6. With this result, 51 dB μV/meter, Figure 2-2 gives a distance of 14 nautical miles which is the interference radius. The process is repeated with the desired and undesired NDB's interchanged and this computation is illustrated in Figure 2-13b. Since the sum of the service and interference radii for Figure 2-13a

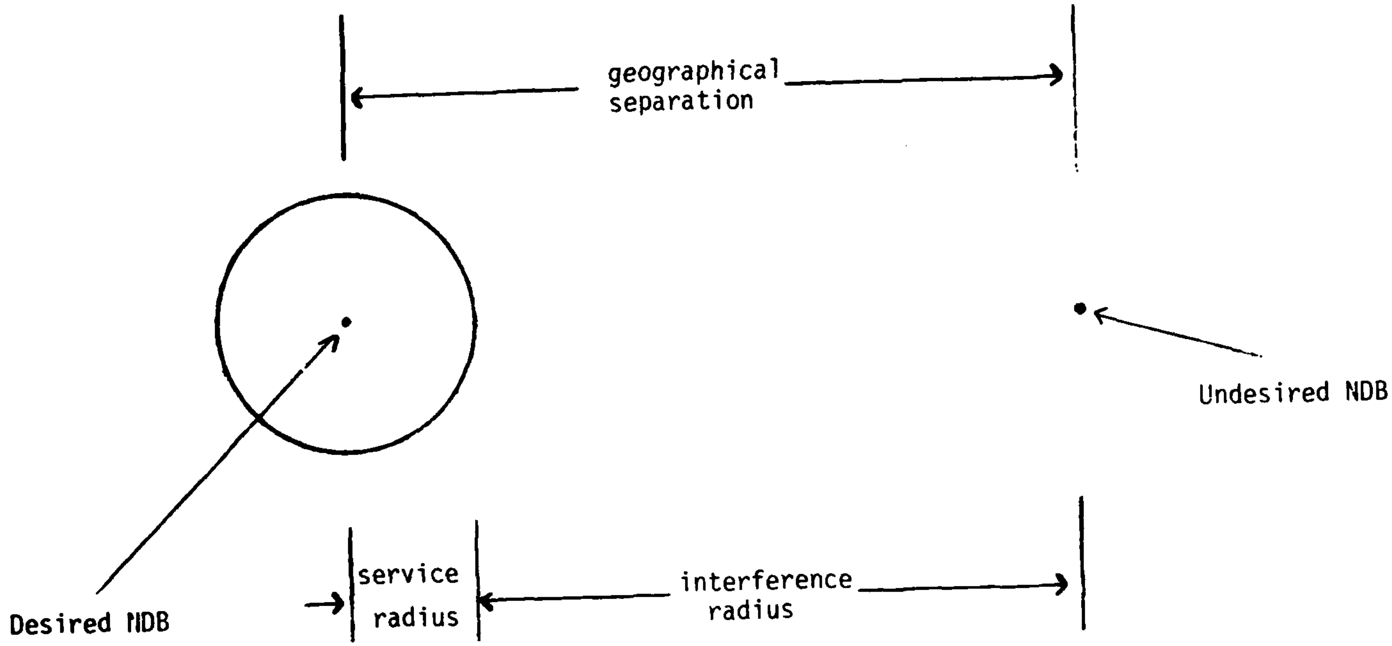

Figure 2-12 Illustration of service radius, interference radius, and geographical separation.

Example 3 - Service and Interference Radii

Desired Signal Level

EIRP = 0.25 watts = -6 dB/1 W (Figure 2-6) (enter also on line 2)

Conductivity = 8 millimhos/meter

Distance to Coverage Limit = 22 Nautical Miles (corresponds to line 1)

Frequency = 345 kHz.

1) Signal at Coverage Limit for 1 kW EIRP (from figures 2-1 through 2-5) — 46 dB/ μV/meter

2) Adjustment to Actual EIRP — -6 dB/ 1 kW

3) Desired (D) Signal Level — 40 dB/ μV/meter

(line 3 = line 1 + line 2)

For 70 μV/m, D must be at least 37 dB μV/meter

Undesired Signal Level

EIRP = 1.6 Watts = +2 dB/1 kW (enter also on line 5)

Conductivity = 8 millimho/meter

Distance to D signal Coverage limit = 14 nautical miles (corresponds to line 4)

Frequency = 341 kHz

4) Signal at D Coverage Limit for 1 / W EIRP — 51 dB/ μV/meter

5) Adjustment to Actual EIRP — +2 dB/ 1 kW

6) Receiver Selectivity Factor (Table 2-1) — -28 dB

7) Effective Undesired (U) Signal Level — 25 dB/μV/meter

(line 7 = line 4 + line 5 + line 6)

8) D - U = 40 (line 3) - 25 (line 7) = 15 dB Interference Margin

For Interference protection, D-U must be at least 15 dB

(all additions must be algebraic)

Figure 2-13a Sample Calculation Number 3.

Example 3 Continued - Service and Interference Radii

Desired Signal Level

EIRP= 1.6 watts = +2 dB/1 W (Figure 2-6) (enter also on line 2)

Conductivity = 8 millimhos/meter

Distance to Coverage LImit = 60 Nautical Miles (corresponds to line 1)

Frequency = 341 kHz.

1)	Signal at Coverage Limit for 1 w ERP (from figures 2-1 through 2-5)	35	dB / μV/meter
2)	Adjustment to Actual EIRP	+2	dB/ 1 W
3)	Desired (D) Signal Level	37	dB / μV/meter

(line 3 = line 1 + line 2)

For 70 μV/m, D must be at least 37 dB μV/meter

Undesired Signal Level

ERP = .25 Watts = -6 dB/1 W (enter also on line 5)

Conductivity = 8 millimho/meter

Distance to D signal Coverage limit = 8 Nautical miles (corresponds to line 4)

Frequency = 345 kHz

4)	Signal at D Coverage Limit for 1 W EIRP	56	dB/μV/meter
5)	Adjustment to Actual EIRP	-6	dB/1 kW
6)	Receiver Selectivity Factor (Table 2-1)	-28	dB
7)	Effective Undesired (U) Signal Level	22	dB/μV/meter

(line 7 = line 4 + line 5 + line 6)

8) D - U = 37 (line 3) - 22 (line 7) = 15 dB Interference Margin

For Interference protection, D-U must be at least 15 dB

(All additions must be algebraic)

Figure 2-13b Sample Calculation Number 3.

is 36 miles, while the sum for Figure 2-13b is 68 miles, the minimum geographic separation is the greater of these sums or 68 miles.

D. Computer Implementation

It appears evident to the authors that the method given above for determining NDB electric field strength and interference margin is simpler to apply than the graphical method given in the current handbook. This is primarily because it is easier to perform additions and subtractions numerically rather than graphically. It is possible, however, that engineers who are familiar with the graphical method might disagree with this point. However, there should be no disagreement with the statement that the new method would be much simpler to use as a basis for a computer program to perform the required determination than the graphical method currently in use. It would be quite simple and straightforward to write a computer program which would prompt the user to enter the necessary information. The program could also be made flexible in its computations quite easily. For example, if the desired signal level at a certain distance were required, the user could enter this distance when prompted to enter the "Distance to the Coverage Limit", and enter an "X" when prompted to enter the "Desired Signal Level". On the other hand, if the rated coverage was desired, the user could enter an "X" when prompted by the computer for the "Distance to the Coverage Limit", and enter 37 when prompted for the "Desired Signal Level in dB μV/meter" (or in μV/meter, if desired).

The only parts of the computation which are not just an algebraic addition or subtraction are the selection of the receiver selectivity for line 6 and the graphical correlation between distance and signal level by application of the appropriate propagation curves, which is

quired to go from the signal levels of lines 1 and 4 to the corresponding distance or vice-versa. The receiver selectivity factor could be obtained in the computer program very easily by merely storing the information in Table 2-1 in the computer and choosing the proper value depending on the frequencies supplied by the user. The propagation curves could be made available to the computer program in two ways. In one, the curves could be sampled and stored in memory, with the program written to interpolate between distance, frequency, and conductivity values to obtain the desired value. Alternatively, the latest CCIR propagation model could be incorporated into or called by the computer program to obtain the electric field strength for specific frequencies, distances, and conductivities. If a distance for a specific electric field strength were desired, it would be simple to develop an algorithm for obtaining the desired distance from the CCIR program given the field strength, since the curves are smooth. The choice of which approach to take would depend on the availability of the CCIR computer program, on computer storage space available, and on cost of computation.

CHAPTER III DETERMINATION OF EFFECTIVE RADIATED POWER

As is evident from the interference computation method outlined in the previous chapter, accurate evaluation of the effective isotropic radiated power of the Non-Directional Beacons under consideration is necessary for an assessment of coverage area and susceptibility to interference. Unfortunately, this is not a simple task, since NDB antennas are generally quite small (in terms of wavelengths) for economic reasons.

It is quite straightforward to accurately measure the transmitter output power. However, to determine the effective isotropic radiated power one also must determine the radiation pattern of the antenna and the antenna efficiency. The former is quite simple, since for the electrically small antennas under consideration the electric field radiation pattern for vertical polarization will always be omnidirectional in the horizontal plane and sin (theta) in the vertical, with theta measured from the vertical. The antenna efficiency, unfortunately, is quite difficult to predict accurately. Many authors give equivalent circuit models for low frequency antennas, with that given by Belrose (6) being typical. His model is a series combination of the following resistances, where it is assumed that the antenna has been tuned to resonance by an inductance:

R_r = radiation resistance

R_g = ground terminal resistance

R_i = insulation loss equivalent resistance

R_w = conductor loss equivalent resistance

R_c = antenna tuning inductance resistance

The total antenna resistance R_t is given by

$$R_t = R_r + R_g + R_i + R_w + R_c \qquad (3\text{-}1)$$

With this model the antenna efficiency is given by

$$\eta = \frac{R_r}{R_t} \times 100\% \qquad (3\text{-}2)$$

If the transmitter output power and antenna system efficiency are both known, then the Effective Isotropic Radiated Power (EIRP) is simply the product of the two times 1.5, the directivity of an antenna with a sin (theta) radiation pattern.

Let us discuss further the terms in Equation 3-1. The radiation resistance can be approximated by formulas or tables. For properly designed antennas in this frequency range (200 to 500 kHz) R_i, the insulation loss, is negligible compared to other terms in the equation. Also, R_w is much less than R_g, and is normally just combined with R_g since it would be quite difficult to measure the two separately. The antenna tuning resistance R_c, while normally less than R_g is not negligible. However, it can be measured, for example, by measuring the power in and out of the matching device between the transmitter and antenna which contains the tuning inductance.

By far the dominant term in equation 3-1 is R_g. In an experimental paper Smith & Johnson (7) present data which indicate that for the frequency range and antenna heights of concern here approximately 90% of the power lost in the antenna and tuner is dissipated in the ground system. Thus an accurate evaluation of R_g is essential for determining efficiency. Unfortunately, R_g seems to depend upon a fairly complex interaction between the ground radial geometry and the finitely conducting ground in the vicinity of the antenna.

Referring again to the paper by Smith and Johnson, his experimental results indicate that there is significant improvement in efficiency as the number of ground radials is increased from an initial few, but that

at some point further increase does not significantly improve efficiency. This number depends upon the length of the radials, and perhaps also on the ground conductivity. Additional experimental data by Nicholson and Collins (8) confirm this observation. At a test site in Colorado with dry, sandy soil, they increased the number of radials by a factor of 2, and found only a 1 dB increase in EIRP. However, while this indicates that more radials do not necessarily increase the EIRP, it does not mean that the radial system entirely removes effects of finite ground conductivity from influence on antenna efficiency. To confirm this point, Nicholson and Collins relate the result of a heavy rain in the area of the above measured test. It would be assumed that this rain would significantly affect the ground conductivity, but not the actual conductors of the ground system. Nevertheless, with the same transmitter output power the EIRP dropped by 4.65 dB after the rain. Evidently, the power lost in the ground system depends on both the radial system and the ground conductivity, with the dependence being a function of, among other parameters, the geometry of the radial system and the ground conductivity.

One possibility is that a theoretical analysis could arrive at this functional relationship. One approach is via the moment method which has been applied successfully to many low frequency problems involving wire antennas (9). In this approach the geometry is fed into a computer, the antenna and ground radial currents are expressed as mode functions of unknown complex amplitude, and boundary conditions are enforced at many points simultaneously to evaluate the unknown amplitudes. This method has been recently extended to geometries involving a conducting half-space (10). However, the antenna and ground system would have to be located entirely in one half-space for the method to apply, that is, the ground radials could not be buried or even touch the ground. Obviously,

this constraint would cast serious doubts on the validity of the results, and at this point it does not seem to be a valid approach.

Wait has developed a closed-form analytical solution to the problem of a vertical antenna over a circular, perfectly conducting disk which is itself located above a finitely conducting half-space (11). The result is fairly complicated, being in the form of sums of Sine and Cosine Integrals, but it could be evaluated using a computer. While the ground screen is not buried, and is modeled as a solid disk rather than as radial wires, it is to the authors' knowledge the best analytical solution available. Unfortunately, there has evidently been no experimental verification of its results. If it were deemed necessary to evaluate the relationship between ground system losses, ground system geometry, and antenna efficiency, then further development and experimental verification of Wait's result might be the best approach to pursue. However, this was considered to be beyond the scope of the present work.

Nevertheless, the Effective Isotropic Radiated Power must be accurately determined in some way for the preceeding, or for that matter, for any interference computation method to be applied. In the authors' opinion, the best way to accomplish this is by measurement of the vertical electric field strength at several points located within a range of approximately 1 to 3 nautical miles from the NDB transmitting antenna. This is far enough from the antenna so that the near fields will not be strongly coupled into the measurement antenna, and close enough so that terrain effects are normally not important. For these conditions, the Effective Isotropic Radiated Power can be easily computed from

$$EIRP = E_m - E_{1\,W} \quad dB/\ 1\ W \qquad (3-3)$$

where

EIRP is Effective Isotropic Radiated Power in dB relative to 1 Watt

E_m is measured vertical electric field strength in dB relative to one microvolt per meter

$E_{1\,W}$ is the predicted electric field strength in dB/1 μV/m at the measurement distance for 1 watt EIRP taken from Figures 2-1 to 2-5 for the appropriate distance and ground conductivity

When the conductivity is fairly good (> 2 millimhos/meter), or when the conductivity is relatively poor but the frequency is low (less than 350 kHz), and the measurement location is less than 2 miles from the NDB, propagation does not depend greatly on the ground conductivity for NDB frequencies, and the electric field attenuates as the reciprocal of distance. For these situations, the propagation curves need not be used and $E_{1\,W}$ is given by

$$E_{1\,w} = 72.4 - 20.0 \log_{10} D_m \tag{3-4}$$

where D_m is the measurement distance in nautical miles. However, if there is any doubt about the applicability of equation 3-4 to a specific situation, it should be checked against the appropriate propagation curve.

If the EIRP is desired in units of Watts, the result of equation 3-3 can be converted to Watts using Figure 2-6.

There has been some discussion in the literature regarding the effects of terrain in the vicinity of the measurement point(s) on the measured electric field strength values. Some recent work by Ohio University involving measurements made in the rolling hills of Southeastern Ohio showed agreement within 2 or 3 dB among measurements made at widely separated points (12). A technical report by Berry et al (13) contains a table of 14 field strength values measured at different points

approximately 1 mile from an NDB located in hilly terrain near Charleston, West Virginia. When adjusted to 1 nautical mile there was a variation of 9 dB from highest to lowest measurement. However, the standard deviation of the 14 values was only 2.35 dB, which compares with the published accuracy of the Fairchild EMC-25 field strength meter of plus or minus 2 dB. A reasonable conclusion is that measured electric field strength values are a dependable means for determining EIRP, but that several measurements at different points should be averaged, especially in hilly terrain.

CHAPTER IV CONCLUSIONS

A new method for the computation of electric field signal strength and interference margin applicable to Non-Directional Beacons (NDB) in the frequency range of 190 to 535 kHz has been presented. While the currently applied method is graphical, the new method requires only algebraic addition and subtraction of decibel values, and is suitable for both hand computation and computer implementation. The new method is fully explained, and several complete examples of its application are given. It is simpler to apply and should be less prone to computational errors than graphical methods.

In addition, analytical and experimental methods for determining the effective isotropic radiated power (EIRP) of an NDB have been discussed. While one analytical approach discussed seemed feasible, at the present time it seems apparent that a process which involves the measurement of the electric field at ground level at several points within 1 to 3 miles of the NDB should be the most accurate and reliable approach and also the simplest to apply. For cases where the ground conductivity is low, especially for higher frequencies, a knowledge of the local ground conductivity will be necessary for accurate results.

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ACRONYMS

ADF	Automatic Direction Finder
CCIR	International Radio Consultive Committee
D	Desired (signal)
dB	decibels
EIRP	Effective Isotropic Radiated Power
FAA	Federal Aviation Administration
kHz	Kilohertz
L/MF	Low/Medium Frequency
NDB	Non-Directional Beacon
U	Undesired (signal)